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EVALUATION OF INFRARED SENSORS FOR
AUTONOMOUS LANDING GUIDANCE



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ELECTRO-OPTICS BRANCH
MISSION AVIONICS DIVISION

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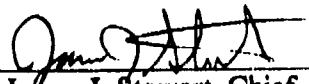
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FOREWORD

This report was prepared by the Electro-Optics Sensors Evaluation/Analysis Group, Electro-Optics Branch, Mission Avionics Division, Avionics Directorate, Wright-Patterson AFB, OH.

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1. Mr Ralph Hoar
2. Mr Clyde Lawrance

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This report was submitted by Mr Absi in April 1993.

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1.0 INTRODUCTION

During April - June of 1992, personnel of the Avionics and Flight Dynamics Directorate, Wright Laboratory, Wright-Patterson Air Force Base, designed and carried out a test to measure the performance of wide field of view infrared cameras during heavy sea fog. The purpose of this test was to determine if infrared cameras could improve the ability of pilots to conduct ground operations (landing, taxi and take-off) during heavy fog. Two midwave platinum-silicide cameras with short focal length lenses were used to represent typical infrared sensors. Tests were conducted at Otis Air National Guard Base (ANGB) in June, at the Otis Weather Test Facility (WTF) operated by the Philips Laboratory (PL/GPAA). The tests measured the range at which a runway could no longer be discerned from the background. Prevailing meteorological conditions were measured by Philips Laboratory personnel during the test period.

2.0 BACKGROUND

Infrared sensors have been widely deployed on military strike aircraft for the past 20 years. These sensors are typically mounted in large external pods or turrets. Use in other aircraft has been nonexistent due to the size, cost, weight, and low mean-time-to-failure of such sensors. The availability of large, two-dimensional infrared focal planes and highly reliable cryogenic coolers and associated electronics has renewed interest in infrared sensors for commercial and military transport aircraft. Declining defense budgets are also motivating sensor manufacturers to find additional applications of infrared technology.

As currently envisioned, a complete autonomous landing system would consist of sensors operating in two or more spectral bands and a high resolution heads-up display (HUD). Flight path information such as altitude, heading, vertical velocity and airspeed would be superimposed on the sensor video. Multiple spectral bands would allow the system to select imagery for highest weather penetration or highest resolution. Sensor data might also be merged with prestored geographical data bases and navigation data from Global Positioning System (GPS) or inertial guidance units. A typical system might use centimeter or millimeter wave radar for initial runway detection and would transition to a high resolution imaging infrared system during the last several hundred feet.

Tests have been ongoing at the Avionics Directorate Tower Test Facility to evaluate various millimeter wave radars and radiometers. Due to geometry limitations very short range tests could not be conducted at Wright-Patterson. Also climatology favored a coastal location versus an inland location for frequent heavy fog. A separate test was planned with the goals of: (1) measuring the short-range capability of infrared sensors, (2) determining the runway/grass thermal contrast versus range for typical fog conditions, (3) determining the infrared extinction versus the visual extinction in typical fogs, (4) determining if vehicles intruding on the runway could also be seen during fog, and (5) determining if common smokes would degrade performance.

3.0 APPROACH

Two coastal locations one in California and one in Massachusetts (Otis ANGB) were initially selected by the Wright Laboratory Staff Meteorologist office as possible candidates for frequent, heavy sea fog during May, June, and July. Otis ANGB was picked due the availability of frequent, automated meteorological data from the WTF. An asphalt pad 62 feet wide and 1500 feet long located near the WTF was used to represent a runway (Figures 1A - 1C). A smoke generator was located but it could not be used due to the proximity of civilian vehicular traffic and the lead time needed to obtain environmental clearance to operate the generator. An armored personnel carrier was obtained approximately halfway through the test and parked on the asphalt pad, but no further heavy fog episodes occurred after the vehicle was obtained.

3.1 DATA COLLECTION APPROACH

The Electro-Optics Branch of the Wright Laboratory operates a 26-ton mobile test van to support sensor and model validation tests at a variety of locations. For this test, a portable shelter was constructed on the roof of the test van. Two sensors and control electronics were mounted in the shelter, 17 feet above ground. Monitors, recorders and digitizers were located in the cabin of the test van. A portable video camera mounted near the sensors was used to document the scene during data collection. To aid in range measurements, small alcohol burners were placed under tin cans at 200-foot intervals along the centerline. Heat from the burners warmed the cans which acted as thermal beacons. The test van was parked 248 feet from the threshold of the runway, along the extended centerline.

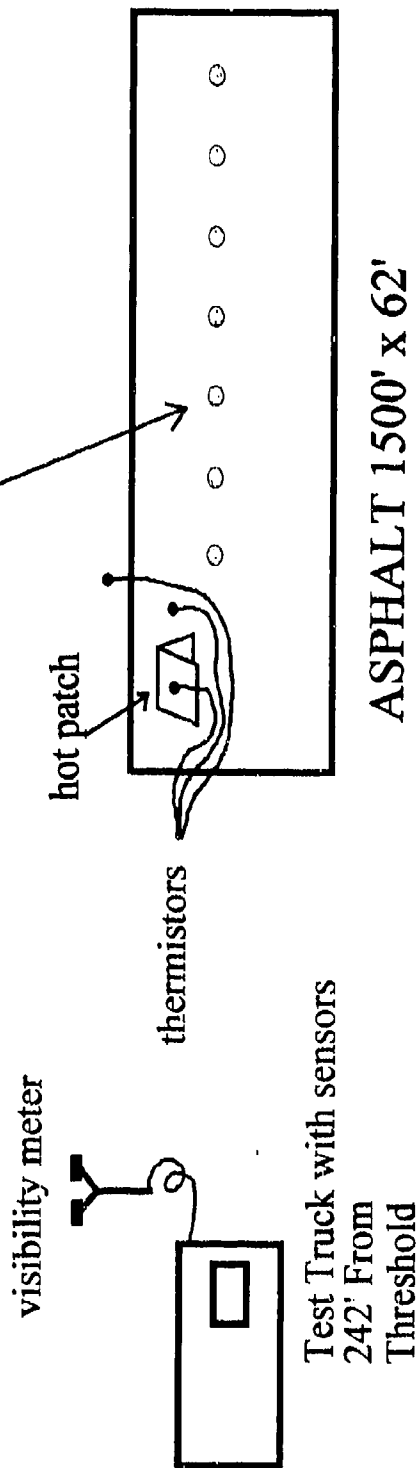
A Mitsubishi 5120C and Kodak KIR-330 platinum-silicide (PtSi) cameras were used throughout the test. Camera specifications are shown in Table 1 (Ref. 1,2). The biggest difference between the cameras is resolution. Due to the short ranges, resolution was not as critical as sensitivity (which depends primarily on f number, lens transmission and pixel area). The test goal was not to compare the two sensors but to see if the measured detection ranges were consistent with their specifications.

Table 1: Sensor Specifications

Parameter	Kodak	Mitsubishi
Field of View	32 X 24 deg	14 X 11 deg
Number of Pixels	640 X 480	512 X 512
NEDT	0.13 °C	0.15 °C
Active Pixel Size	18 x 18 um	16 x 14 um
f number	1.8	1.2
focal length	27.5 mm	50 mm

Meteorological measurements were made at 10-minute intervals, and at 55 minutes past the hour, throughout the test period by the WTF. These consisted of air temperature, dewpoint, visibility, cloud cover, barometric pressure, wind speed, and wind direction. Due to the patchy nature of fog, visibility measurements were also made near the test van by Wright Laboratory personnel using an HSS VF-500 forward scatter meter. The VF-500 has an accuracy of +- 5 percent over a range of 0-16 km visibility (Ref. 3).

THERMAL MARKERS @ 200' SPACING



ASPHALT 1500' x 62'

Figure 1A: Otis ANGB Test Layout



Figure 1B: Side View of Test Truck



Figure 1C: Visible Image of Test Area

In order to obtain radiometric measurements, the sensor video had to be calibrated. This was accomplished by imaging two Eppley BB-103 blackbodies immediately after each measurement. Postprocessing of the imagery converted video intensity to temperature.

Physical measurements of the runway and grass temperature were made using thermistors. One thermistor was epoxied to the asphalt surface, another was placed in grass to the left of the runway. These thermistors were read after each measurement sequence. Finally, a 3-foot-square thermal source was placed in the field of view. This source consists of an electrically-heated rubber pad bonded to a sheet of flame-sprayed aluminum. The aluminum surface was painted flat black to reduce its reflectance in the visible and infrared. Surface temperature of the thermal source was also measured using thermistors (Ref. 4).

4.0 TEST RESULTS

The sensors and associated equipment were set up at Otis on 5 June. Data collection began on 6 June, and data were collected whenever visibility was forecast to be below 1/2 mile. The best data were obtained on 6, 7, and 8 June, although some data were collected on 15 and 20 June. Colder than normal weather on the eastern seaboard limited the occurrence of fog at Otis during the month, however on one day (7 June) visibility dropped to under 200 meters. On the other days, visibilities of 770 meters and 304 meters were recorded by the forward scatter meter.

4.1 Data Collection, 6 June 1992

The first data collection occurred on 6 June. The lowest visibility (770 meters) was recorded at 1219 EDT. The WTF measured an air temperature of 17.2 °C, a relative humidity of 97 percent and a barometric pressure of 980 mbar. The wind was from 170 degrees at 3.1 m/s. The sky was overcast and the ceiling was indefinite, obscured by fog. The 3-foot thermal source was set at 29 °C. No thermistor data for the runway and grass were available for this day's data collection. An inherent temperature contrast of 3.3 °C was calculated from the video imagery.

Figures 2 and 3 show the scene as seen by the Kodak and Mitsubishi camera respectively. The entire runway is seen in both images, but there is a loss of contrast towards the end of the runway.

4.2 Data Collection, 7 June 1992

The second data collection occurred on 7 June. The lowest visibility (190 meters) was recorded at 0054 EDT. The WTF measured an air temperature of 14.4 °C, a relative humidity of 96 percent and a barometric pressure of 984 mbar. The wind was from 260 degrees at 2.6 m/s. Once again the sky was overcast and the ceiling was indefinite, obscured by fog. The 3 foot thermal source was set to 17.8 °C. The thermistor readings on the asphalt and grass were 19.2 and 17.0 °C respectively.

Figures 4 and 5 show the scene as recorded by the Kodak and Mitsubishi cameras. No camcorder imagery was recorded since data collection occurred at night. The runway is visible out to the fourth marker in both IR images. This corresponds to a distance of approximately 1050 feet.

4.3 Data Collection, 8 June 1992

The third data collection occurred on 8 June. The lowest visibility (304 meters) during the test period occurred at 1937 EDT. The WTF measured an air temperature of 17.2 °C, a relative humidity of 89 percent and a barometric pressure of 978 mbar. The wind was from 220 degrees at 6.2 m/s. The three- foot thermal source was set at 20.0 °C. The thermistor readings on the grass and asphalt were 19.4 and 24.9 °C respectively.

Figures 6 and 7 show the image from the Kodak and Mitsubishi cameras. The entire runway is visible, and there is little apparent degradation in contrast at the extreme end of the runway.

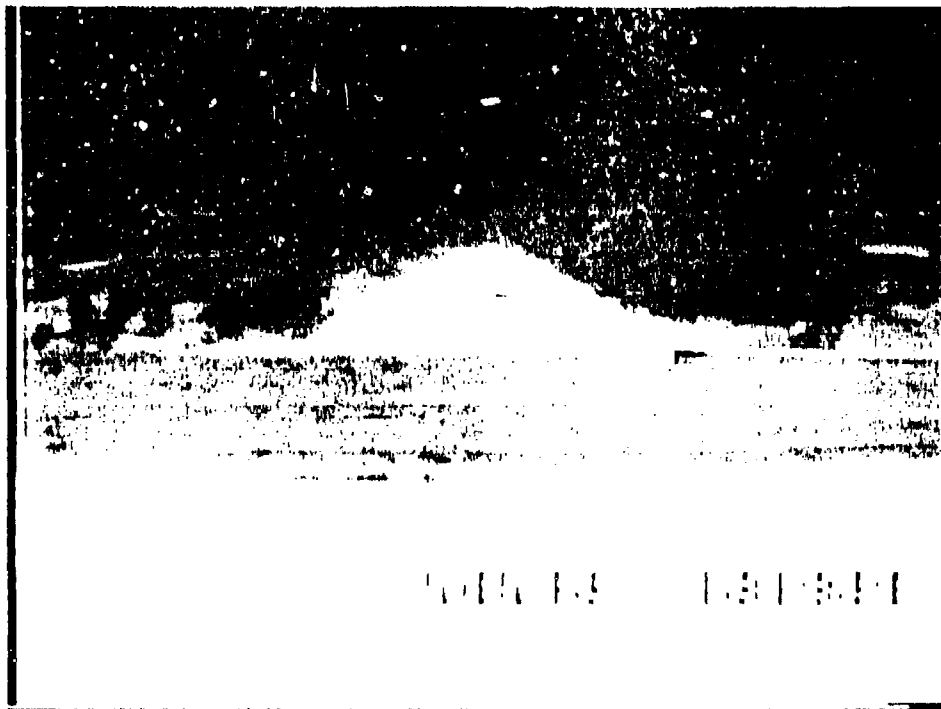


Figure 2: Kodak Sensor Image, 6 June 92.

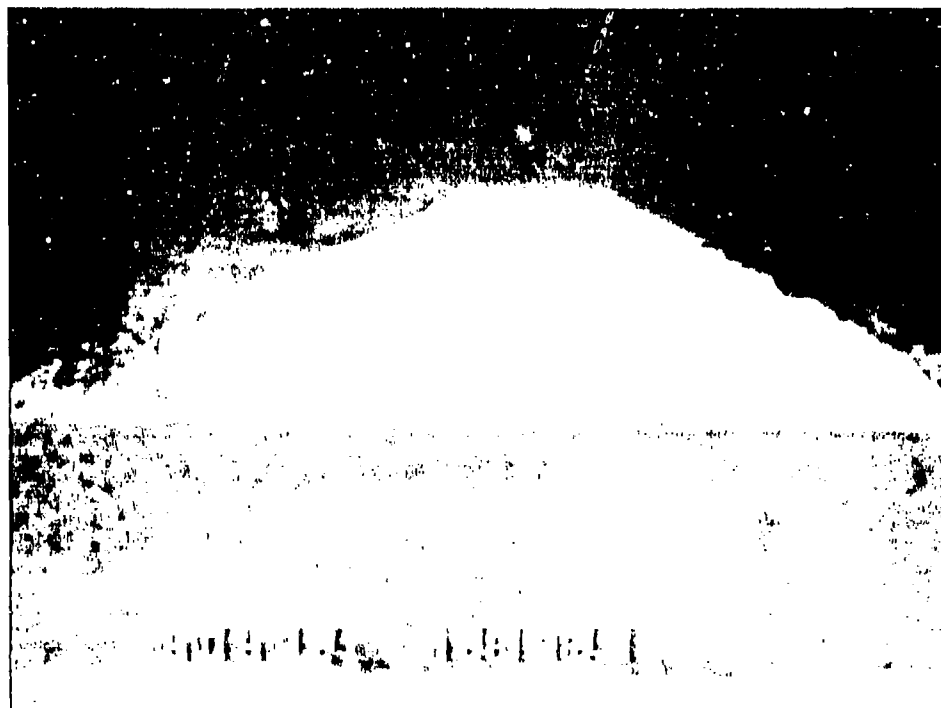


Figure 3: Mitsubishi Sensor Image, 6 June 92.

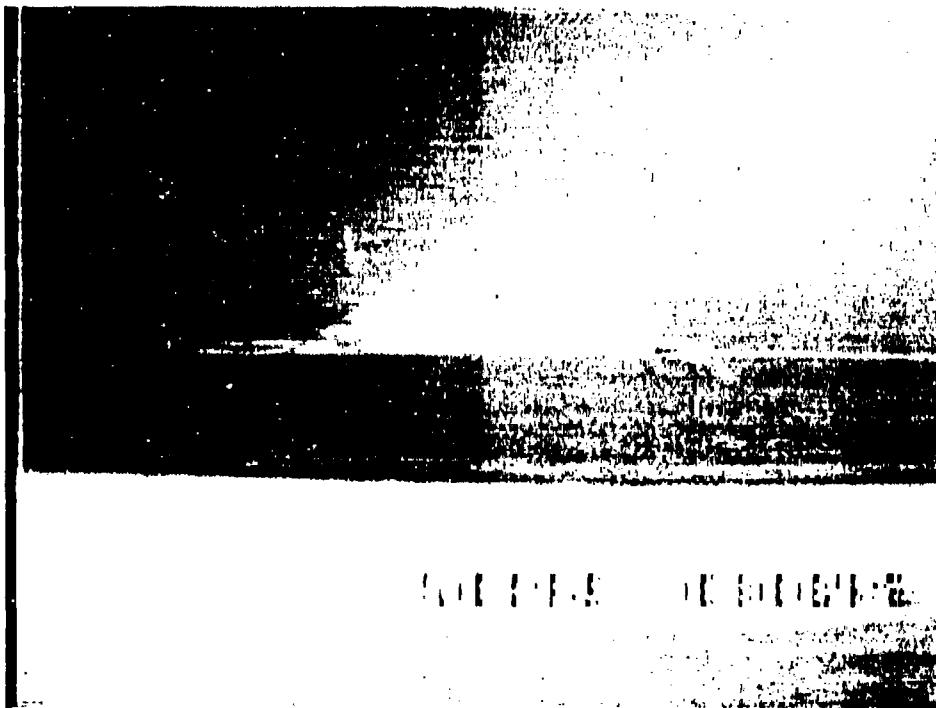


Figure 4: Kodak Sensor Image, 7 June 92.

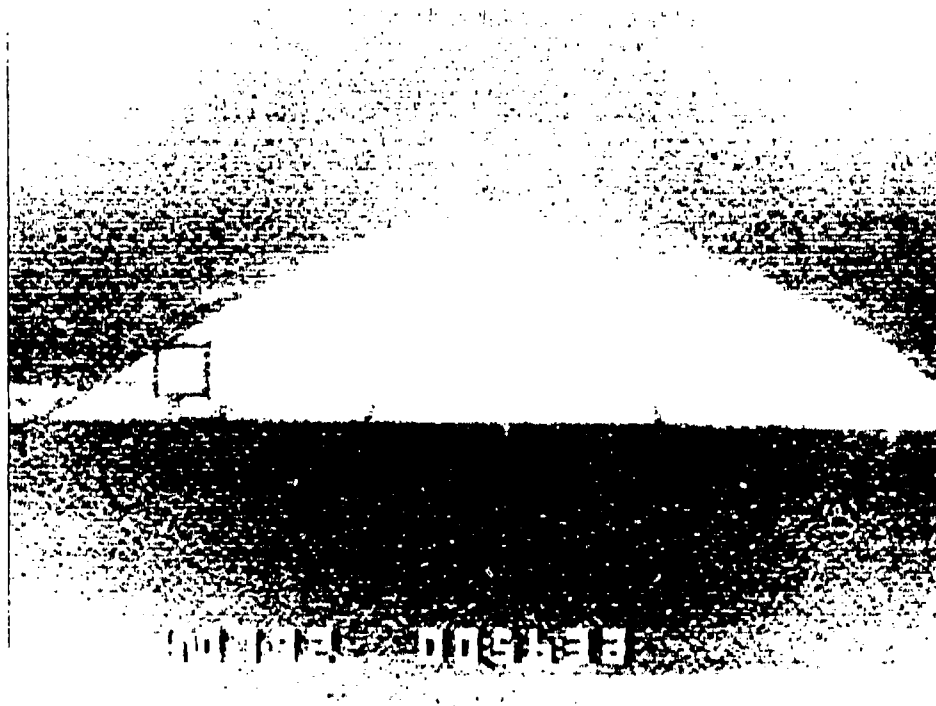


Figure 5: Mitsubishi Sensor Image, 7 June 92.

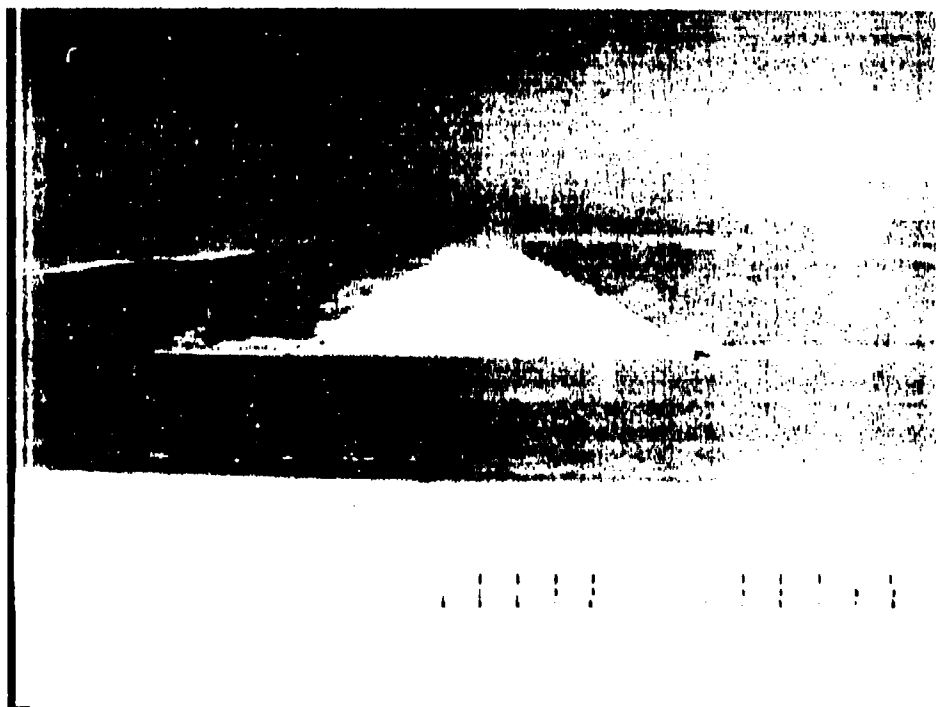


Figure 6: Kodak Sensor Image, 8 June 92.



Figure 7: Mitsubishi Sensor Image, 8 June 92.

5.0 DATA ANALYSIS APPROACH

The sensor, runway and grass temperatures, and atmosphere are the three factors that must be considered during the analysis. The sensors were characterized by their Minimum Detectable Temperature (MDT). Since the sensors were calibrated, both radiometric and surface temperature data for the runway and grass are available. No direct measurement of atmospheric transmission is available, however, the Avionics Directorate Staff Meteorologist computed the path radiance and transmission versus range for each of the three data collection episodes.

An indirect measure of transmission can be derived from the change in runway temperature versus range, or from the change in contrast versus range. Once these factors are known, a range equation must be developed. To develop this range equation a relation between the target and sensor must be found. The sensor MDT is a function of temperature and target size in milliradians. The runway/grass contrast and the apparent size of runway vary with range. By combining the contrast and apparent size into one curve a graphical solution to the range can be easily found.

To solve the range equation graphically, the contrast versus range and runway width versus range are plotted on the same graph (see Figure 8). This graph shows that there is a unique width and temperature for each range. These points are then used to construct the runway width versus temperature contrast curve as shown in Figure 9. Finally, sensor MDT is plotted on the same graph as shown in Figure 9. In the example shown, the MDT and contrast curves intersect at 55 milliradians. For the runway to subtend a width of 55 milliradians the range must be 1400 feet. This technique is used in Section 6 to analyze the data. First, however, the individual MDT curves must be measured.

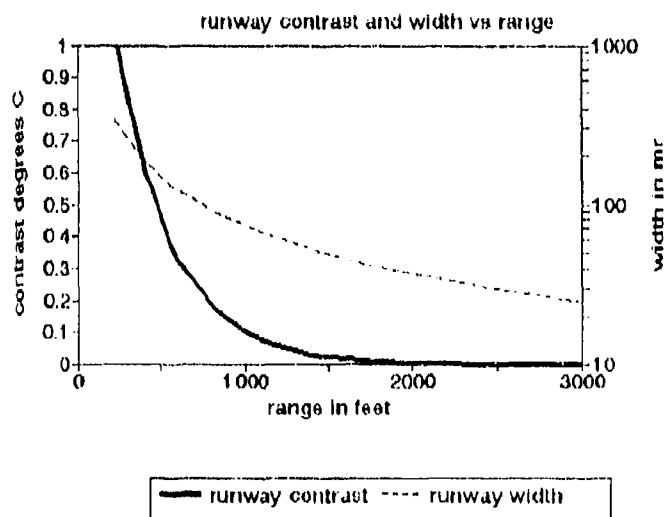


Figure 8: Sample Runway Contrast and Width

5.1 Sensor

Sensor MDTs were measured in the Avionics Directorate Infrared Laboratory. The resultant data are shown in Figure 10. The Mitsubishi sensor was operated in the MANUAL LEVEL mode, with the gain set at 5 (maximum gain). The Kodak sensor was set for a gain of 5.3, offset of 0.1, histogram projection off, offset and gain correction on.

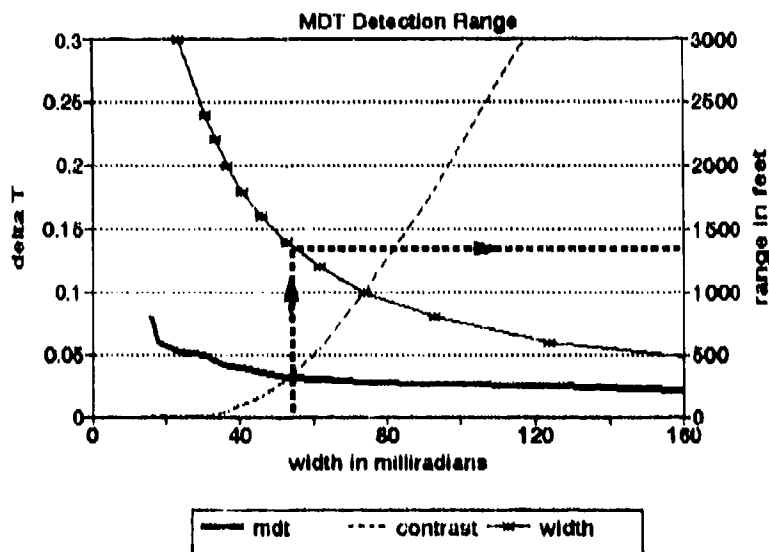


Figure 9: Sample MDT Detection Range Calculation

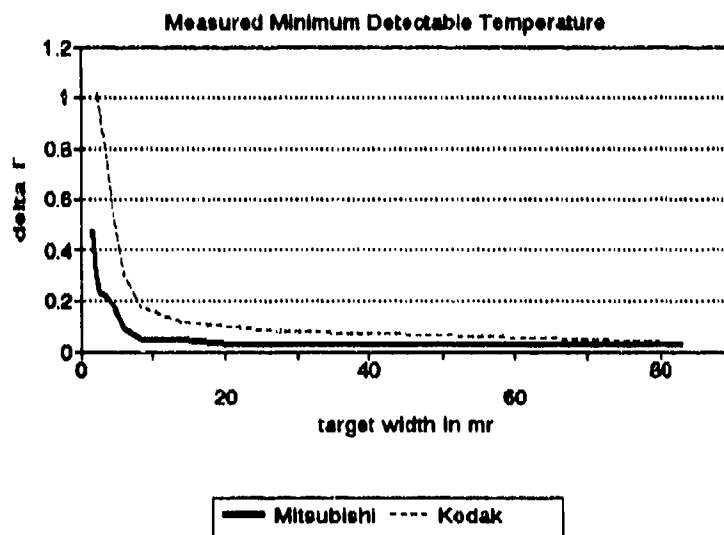


Figure 10: Measured Minimum Detectable Temperature

5.2 Target

As mentioned above, both sensors were calibrated with full-field images of reference blackbodies after each data collection. After the test the video data was digitized and converted from video intensity to radiometric temperature. Horizontal lines of video corresponding to 100 foot range increments were then extracted from the full frame using commercial spreadsheet software. Typical curves for both sensors at ranges of 300, 600, 900, 1200, and 1500 feet is shown in Figures 11 and 12. Because of atmospheric attenuation, the temperature curves will stack on top of one another with the nearer ranges on top. The spikes near the center of some of the plots are due to the thermal markers. Also apparent in the 300-foot plot is the hot patch; it's the highest "plateau" near the left side of the plot.

Apparent thermal temperatures from the hot patch were compared to thermistor values from the hot path as a first-order check of the data. Runway-grass contrast was calculated by subtracting the temperature at pixel $n - 9$ from the temperature at pixel n . This value peaks near the runway edges. A typical curve is shown in Figure 13.

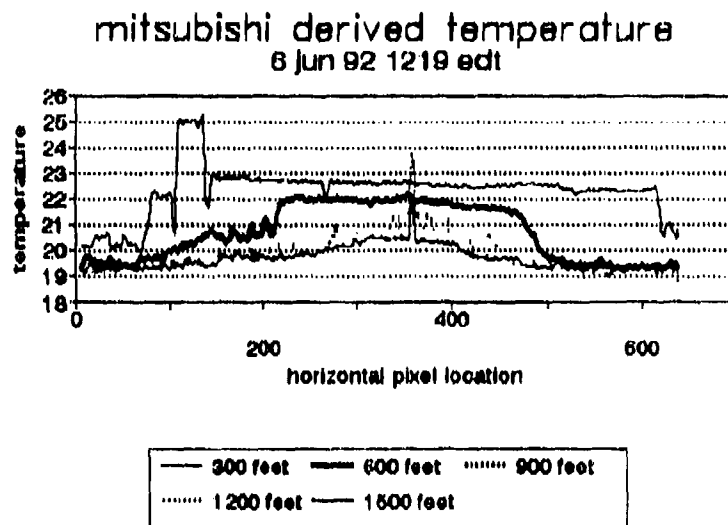


Figure 11: Mitsubishi Camera Typical Temperature versus Range

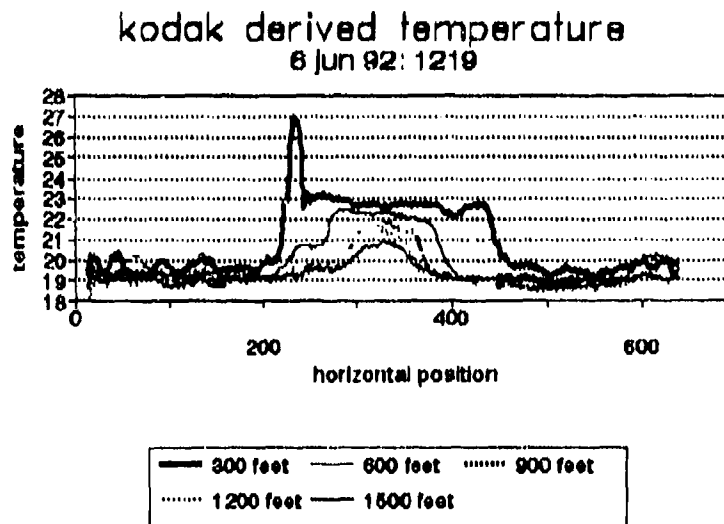


Figure 12: Kodak Camera Typical Temperature versus Range

Measured surface temperatures were compared to surface temperatures predicted by the Thermal Contrast Model 2 (TCM2). TCM2 is an advanced infrared signature code that uses a three dimensional finite difference thermal analyzer and multisurface radiosity method for deriving high resolution signatures. TCM2 was developed by Georgia Institute of Technology Research Institute (GTRI) under contract to the Air Force. TCM2 predicts the infrared signature and surface temperature of man-made objects and natural backgrounds (Ref. 5).

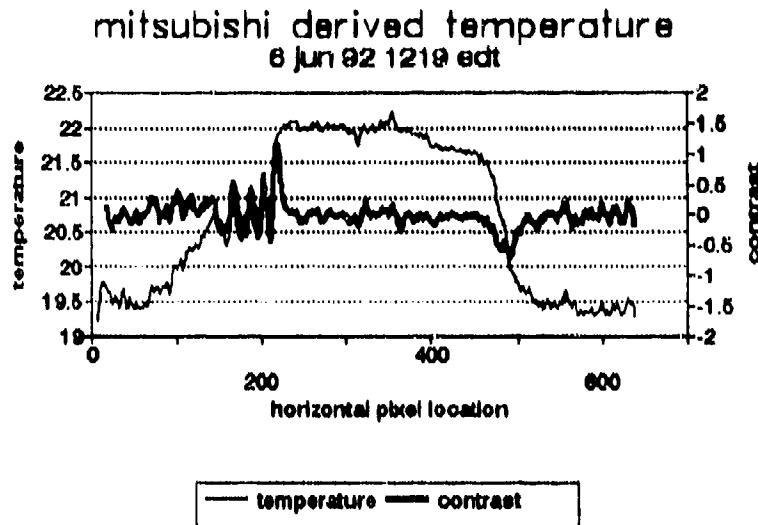


Figure 13: Typical Temperature and Contrast Plot

TCM2 has a number of "first principles" background models. The models of interest to this effort are the foliage, asphalt and concrete models. A number of types of asphalt, such as interstate road, parking lot, or runway can be chosen. These choices change the total thickness and number of thermal nodes. The asphalt model also allows the user to select new or aged surface condition. Changing the surface condition varies the solar absorptivity from 0.93 (new) to 0.85 (aged) (Ref. 6).

Examination of camcorder video imagery of the Otis surface shows that the asphalt is actually lighter (less absorptive) than the foliage (the foliage solar absorptivity is 0.76). Several test runs showed that the model was most sensitive to changes in absorptivity as would be expected. For example changing from new to aged asphalt made a 0.5 °C change to the predicted temperature using the 7 June weather data. There is currently no way to input a user-defined absorptivity into the background models.

Parameters for concrete were examined to determine if the concrete model might be more applicable to the Otis surface. The concrete model uses an absorptivity of 0.64. All other parameters except for thermal conductivity were identical. To determine the effect of thermal conductivity several runs were made comparing asphalt and concrete runway surfaces. Fortunately, the model allows the user to select new asphalt with a solar absorptivity of 0.93 and black-colored concrete with a solar absorptivity of 0.91. The difference between the two was less than 0.2 °C for the 7 June weather data and about 1 °C for the 6 and 8 June weather data. Therefore, results from the asphalt and concrete models were averaged to create a more generic surface. It was also found that the class of asphalt did not produce as much of a change in the results. For example switching the model from "Runway" to "Interstate Road" asphalt produced about a 0.1 degree change in the predicted temperature using the 7 June weather data. The "Interstate Road" selection was used for all model runs.

5.3 Atmosphere

The Avionics Directorate Staff Meteorologists ran MODTRAN, a computer model developed by the Air Force Geophysics Directorate that predicts atmospheric transmission and path radiance as a function of path length, aerosol type, and weather. All runs were made at 3.5 microns as a

representative band-average value. All runs were made with the advection fog aerosol model.

To calculate transmission, the change in runway/grass contrast versus range is used since at any range x the difference in radiance L is:

$$dL_x = (\tau L_{r\text{ inherent}} + L_{\text{path}}) - (\tau L_{g\text{ inherent}} + L_{\text{path}})$$

where the subscripts r and g refer to the runway and grass respectively, and τ is the transmission over the path of interest.

By taking the ratio $\frac{dL_2}{dL_1}$ where the subscripts 1 and 2 refer to two different ranges, the extinction coefficient can be derived as shown below:

$$\frac{dL_2}{dL_1} = \frac{\tau_2(L_{r\text{ inherent}} - L_{g\text{ inherent}})}{\tau_1(L_{r\text{ inherent}} - L_{g\text{ inherent}})}$$

Then by substituting Beer's Law for τ :

$$\frac{dL_2}{dL_1} = \frac{e^{-\alpha R_2}}{e^{-\alpha R_1}}$$

where α is the extinction coefficient.

$$\ln \frac{dL_2}{dL_1} = \alpha(R_1 - R_2)$$

$$\alpha = \frac{1}{(R_1 - R_2)} \ln \left(\frac{dL_2}{dL_1} \right)$$

6.0 DATA ANALYSIS RESULTS

6.1 Results, 6 June 1992

The Mitsubishi and Kodak detection range graphs are shown in Figures 14 and 15. The Mitsubishi sensor MDT curve and runway temperature curve intersect at 20 milliradians. This yields a detection range for the Mitsubishi sensor of 3000 feet. This indicates a measurable improvement since the visibility at the time was 2500 feet. The Kodak sensor MDT curve and runway temperature curve intersect at 25 milliradians. This yields a detection range for the Kodak sensor of 2600 feet. The calculated infrared extinction coefficient was 0.0015 inverse feet which compares well with the MODTRAN-calculated value of 0.0013. The model-calculated temperature difference was 4.6 °C versus the measured value of 3.3 °C.

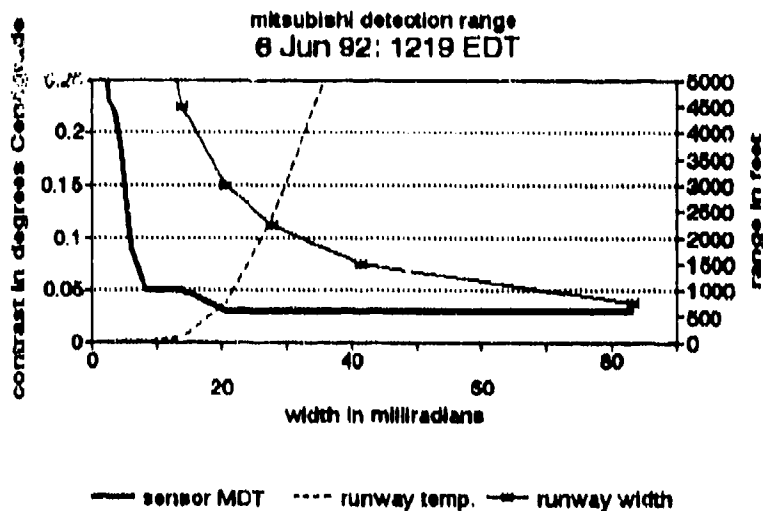


Fig 14: Mitsubishi Detection Range, 6 June 1992

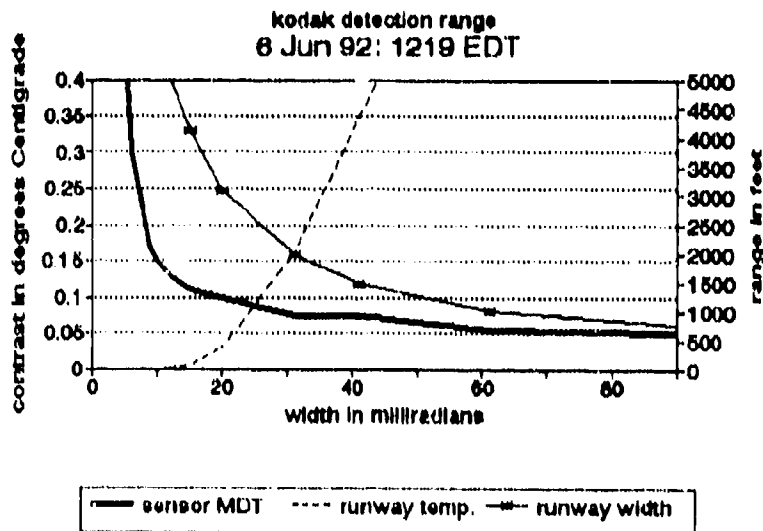


Fig 15: Kodak Detection Range, 6 June 1992

6.2 Results, 7 June 1992

The Mitsubishi detection range graph is shown in Fig 16. The sensor MDT curve and runway temperature curve intersect at 55 milliradians. This yields a detection range of 1200 feet. As shown in Figure 17, the Kodak sensor MDT curve and runway temperature curve intersect at 65 milliradians, yielding a detection range of 1000 feet. This is a significant improvement since the visibility at the time was 630 feet. The MODTRAN-calculated infrared extinction coefficient was 0.005 inverse feet, compared to a measured extinction of 0.004. The measured surface temperature contrast was 2.2 °C versus a model-calculated value of 2.6 °C. The measured grass and runway temperatures were 17.0 and 19.2 °C respectively versus the calculated values of 17.2 and 19.8 °C.

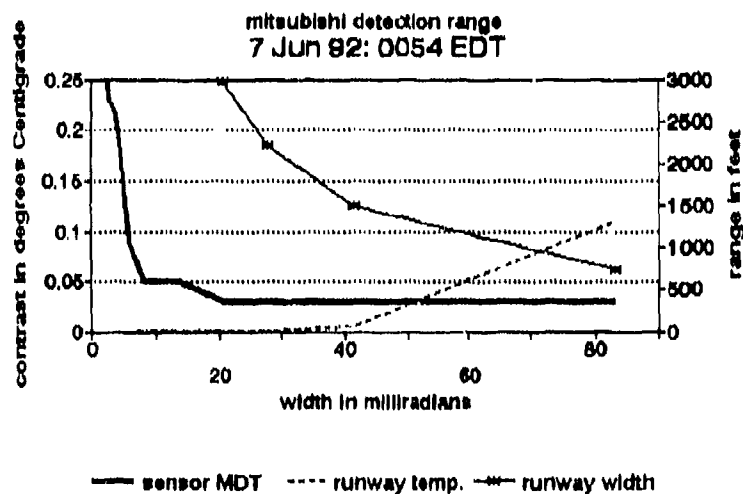


Fig 16: Mitsubishi Detection Range, 7 June 1992

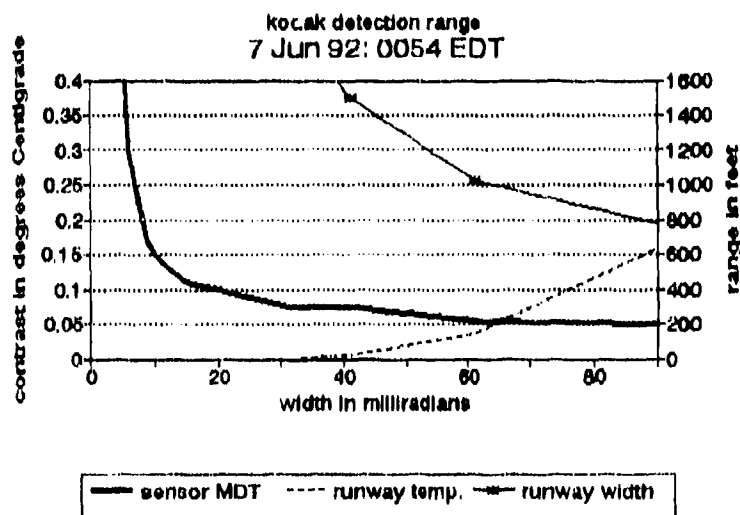


Fig 17: Kodak Detection Range, 7 June 1992

6.3 Results, 8 June 1992

The Mitsubishi and Kodak detection range graphs are shown in Figures 18 and 19 respectively. The Mitsubishi MDT curve and runway temperature curve intersect at 6 milliradians. This yields a detection range of 10,000 feet. The Kodak's MDT curve intersects the runway temperature curve at 7.5 milliradians, yielding a detection range of 9500 feet. This is a significant improvement since the visibility at the time was 1000 feet. The calculated infrared extinction coefficient was 0.0004 which is almost an order of magnitude better than the MODTRAN-calculated value of 0.003 inverse feet. The measured contrast was 5.5 °C versus the calculated value of 7.1 °C. The measured grass and runway temperatures were 19.4 and 24.9 °C respectively versus the calculated values of 17.8 and 24.9 °C.

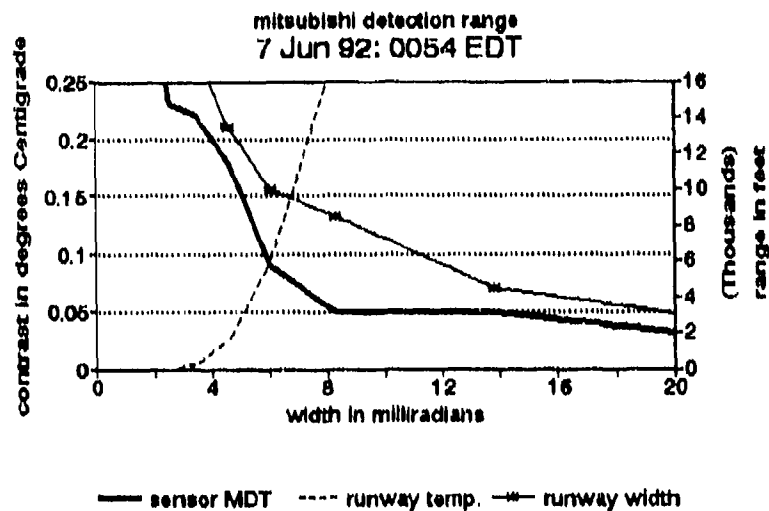


Fig 18: Mitsubishi Detection Range, 8 June 1992

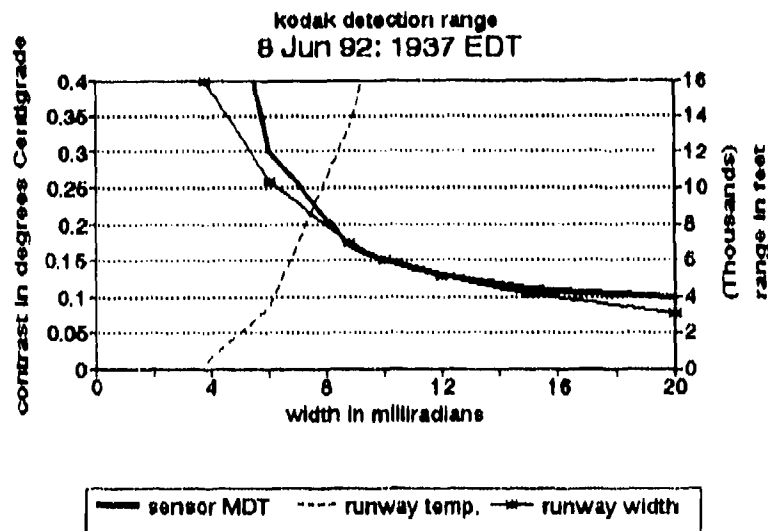


Fig 19: Kodak Detection Range, 8 June 1992

7.0 CONCLUSIONS

7.1 Utility of Infrared Imagers for Autonomous Landing

The two PtSi sensors used during the test provided an image of the runway at ranges greater than the measured visibility. During the lowest visibility condition, the sensors provided approximately 40 percent improvement. Other infrared sensor technology such as InSb and HgCdTe can provide MDT's of 0.01 °C at the spatial frequencies of interest. This would raise the detection range from 1000 to 1500 feet for the lowest visibility data.

7.2 Utility of MODTRAN For Performance Calculations

These data sets indicate that MODTRAN works fairly well when the weather conditions cause the path radiance or transmission to dominate sensor performance (6 and 7 June data respectively). MODTRAN has serious problems when the atmospheric limitations are caused by a mix of path radiance and transmission. For example using the MODTRAN-calculated extinction coefficient with the 8 June data drops the calculated detection range from 10,000 to 2,000 feet!

7.3 Use of MDT For Performance Calculations

MDT worked extremely well for the performance calculations. It's interesting to note that under most conditions sensitivity at the large target widths is the factor that determines detection range.

7.4 Use of Imaging Sensors for Transmission Measurements

The data reduction techniques presented above demonstrate that first-order estimates of infrared extinction coefficient can be derived from infrared imagery.

7.5 Use of Analytical Thermal Signature Models

Determining the utility of an infrared sensor for landing applications requires accurate models. The model used in this analysis provided reasonable estimates of thermal contrast under the lowest visibility conditions. To improve model accuracy the foliage model parameters should allow selection of trees, shrubs, and grass. Analysis conducted by GTRI shows that the use of a generic foliage model can introduce errors of 2 °C in the summer and 1 °C in the winter for typical continental U.S. locations. Knowing the solar absorptivity was more critical than knowing the exact thickness of the runway surface. Future tests where analytical modeling is required should measure the solar absorptivity of the surface. This could be accomplished by simultaneously measuring the upwelling and downwelling irradiance using broadband pyranometers

8.0 REFERENCES

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